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Title: Development of Computational Tools for Laser and Electron Beam Welding

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Development of Computational Tools for Laser and Electron Beam Welding

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Background

- Defense and aerospace applications commonly utilize laser beam welding (LBW) and electron beam welding (EBW) to join highly critical joints

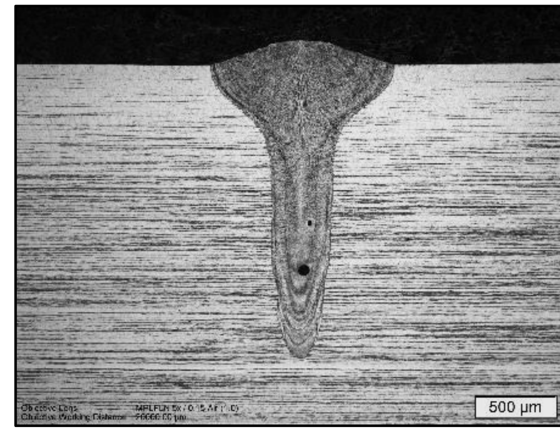
Materials of interest include:
  - 304L Stainless Steel
  - Ti-6Al-4V
  - Refractory Alloy

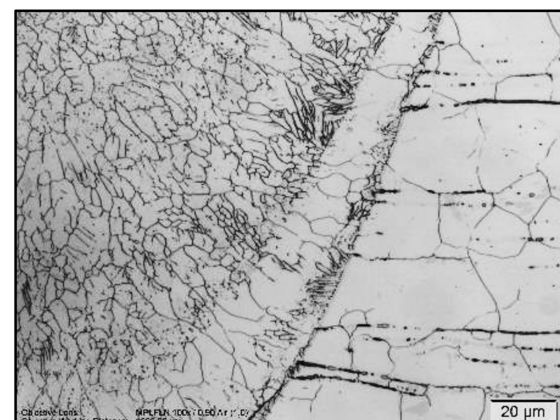
https://phys.org/news/2019-07-earth-mars-days-power-nuclear.html

- Joint configurations are not always susceptible to post-weld inspection

Background

- Need to validate weld characteristics given parameter inputs
  - Weld dimensions
    - Penetration depth
    - Keyhole width
    - Cross-sectional area
  - Thermal History
    - Microstructural evolution



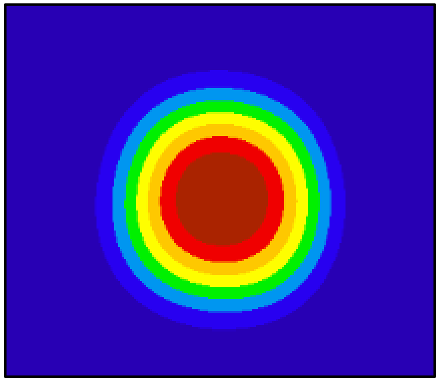


- How do process parameters influence weld geometry and microstructural formation

Background

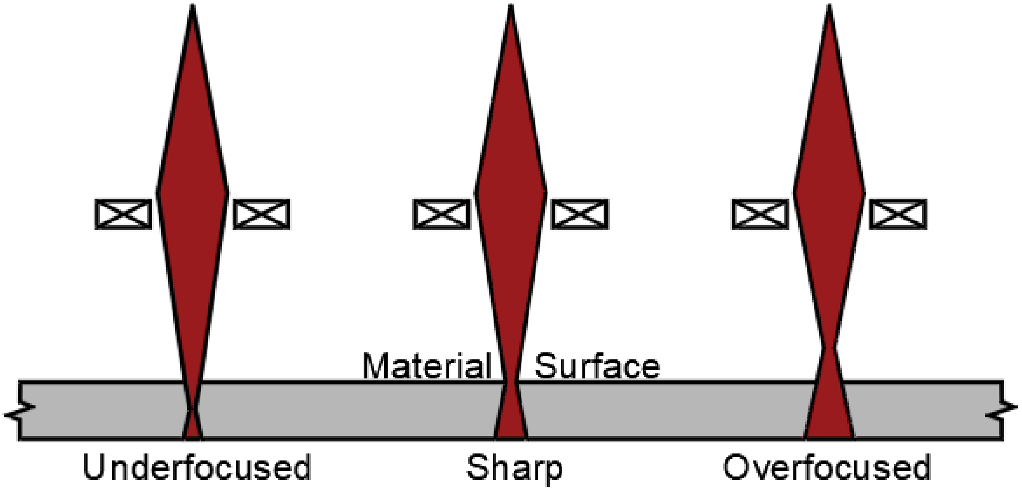
Process Parameters

- Power
  - Voltage and Current (EBW Only)
- Travel Speed
- Focus position
- Beam Diameter
- Beam Profile (intensity distribution)



Material Properties

- Density
- Thermal Conductivity
- Specific Heat
- Thermal Diffusivity



Background

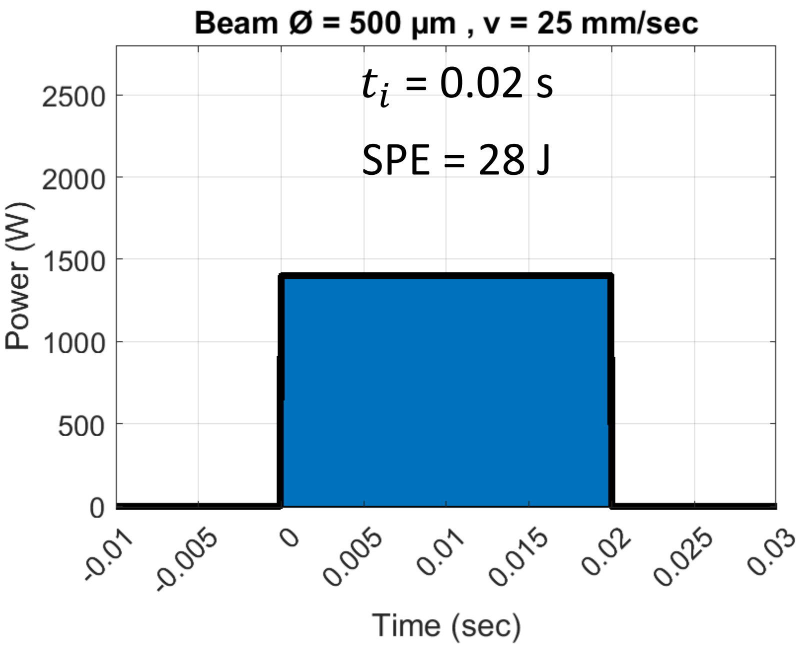
Beam Parameter Manipulation

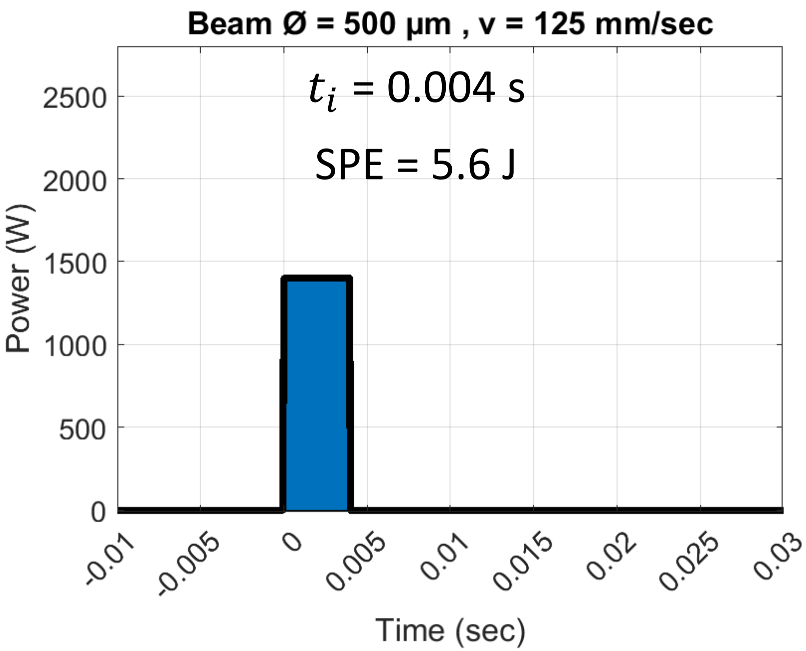
- Interaction Time and Specific Point Energy

$$t_i = {}^{d_b}/_{v} \qquad [s]$$

$$\mathrm{SPE} = \mathrm{P} * t_i \qquad [J]$$

Where: d_b = beam diameter
v = travel speed
P= beam power



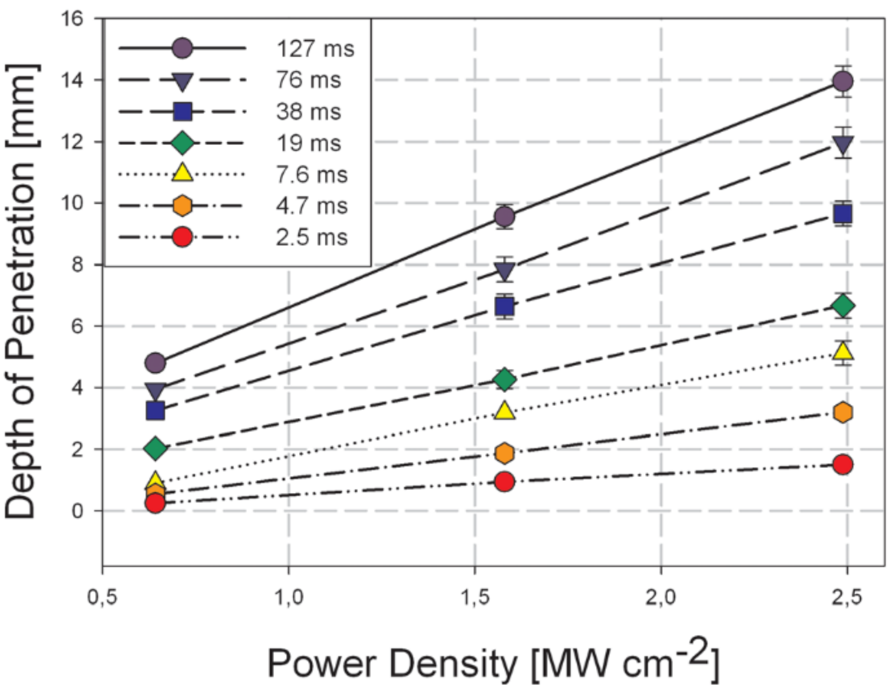


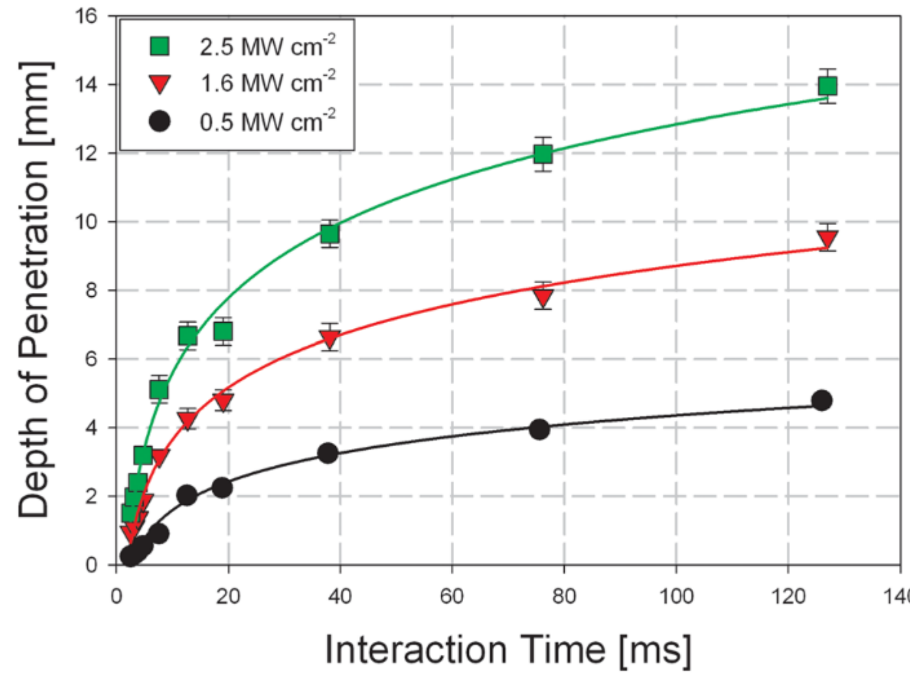
Literature Review

Suder and Williams, 2012 [1]

- Top-hat beam distribution
- YLR-8000 IPG laser

Beam diameter = 630 µm

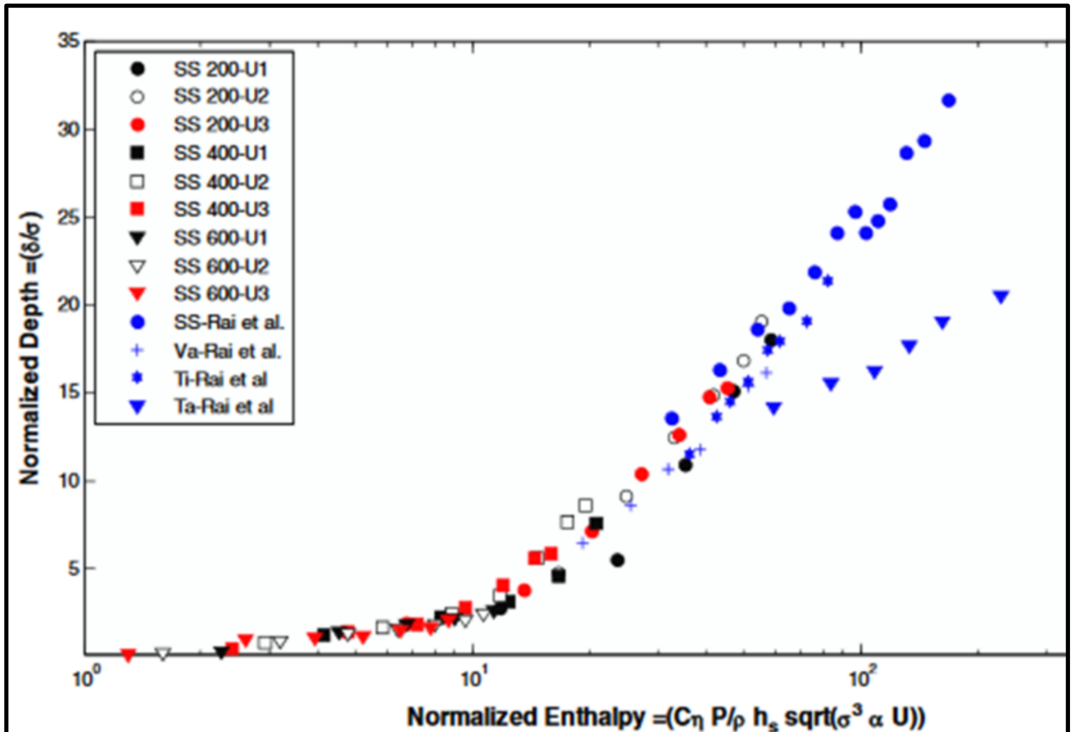




Literature Review

Hann et. al, 2011 [2,3]

- Incorporation of input parameters and material properties to predict penetration depths



Dimensionless depth

$$\delta^* = f\left(B\frac{P}{\sqrt{\sigma^3 U}}\right)$$

$$\delta^* = f\left(\frac{\Delta H}{h_s}\right)$$

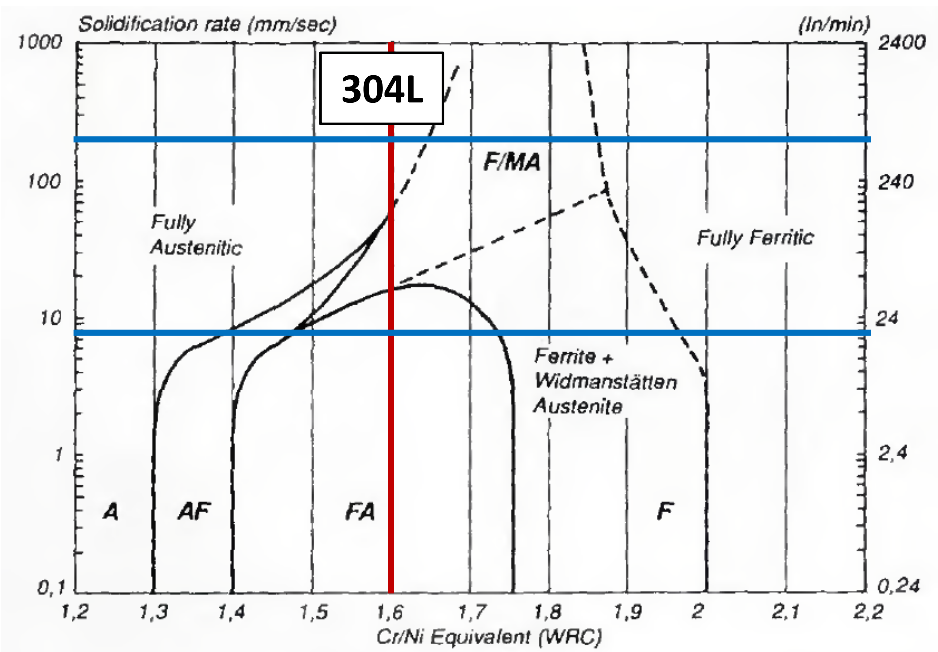
Where:

δ : depth of penetration
δ* : normalized depth
σ : beam radius
B : normalization constant
P : power
U : travel speed
$\boldsymbol{\Delta H}$: change in enthalpy
$\boldsymbol{h_s}$: enthalpy at melting

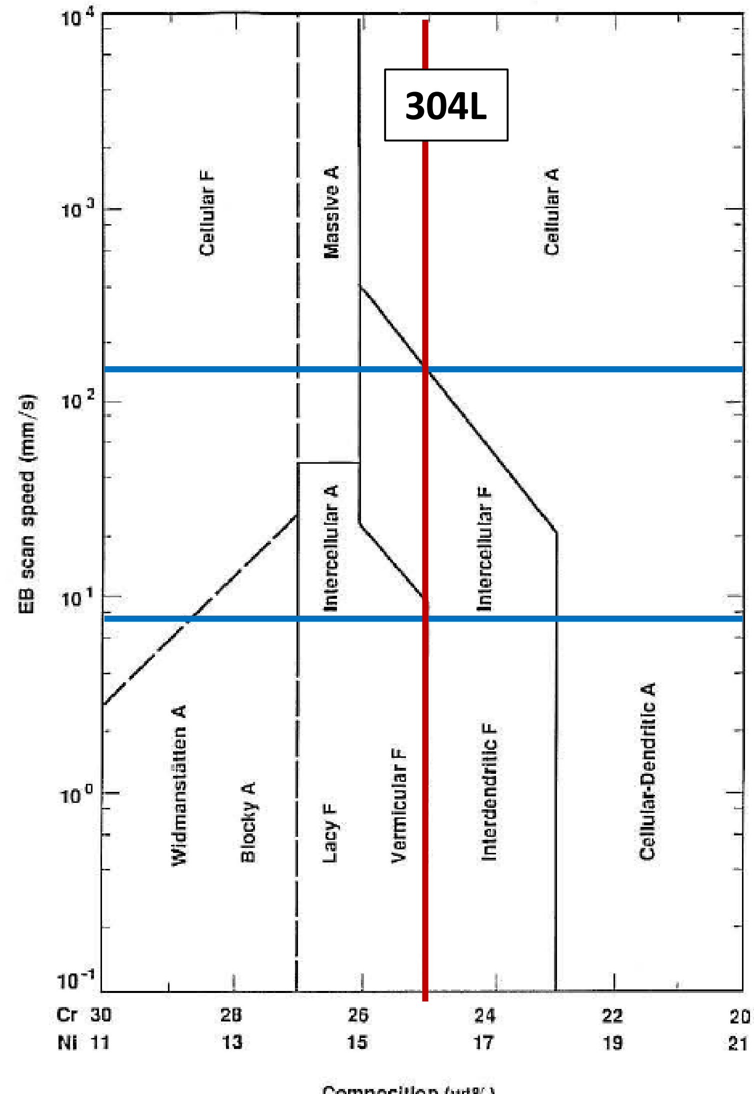
Literature Review

Lippold, 1994 [4]; Elmer et al., 1989 [5]

- Influence of input parameters on solidification modes and microstructure



[4]



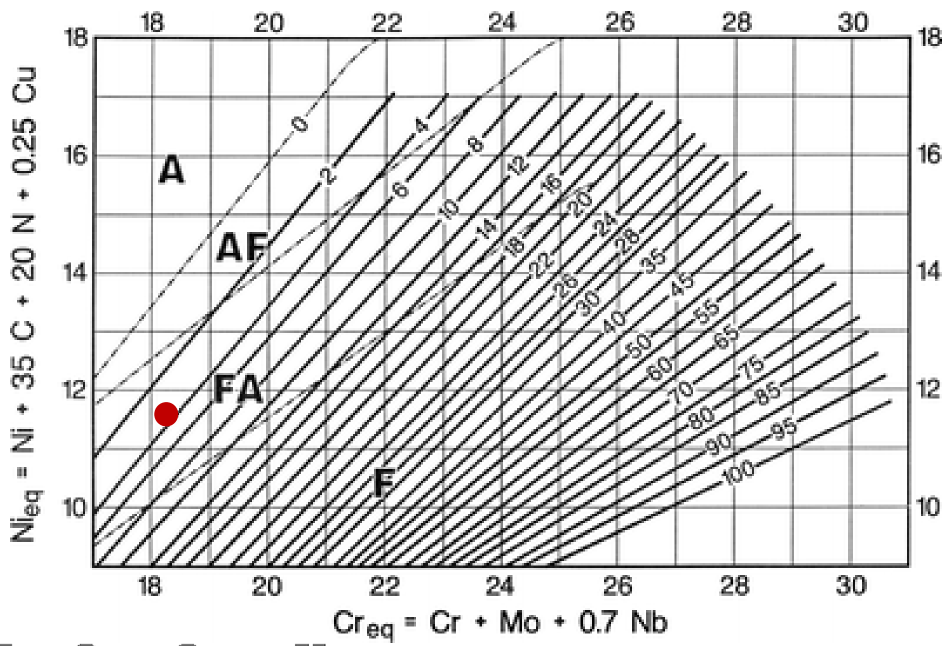
[5]

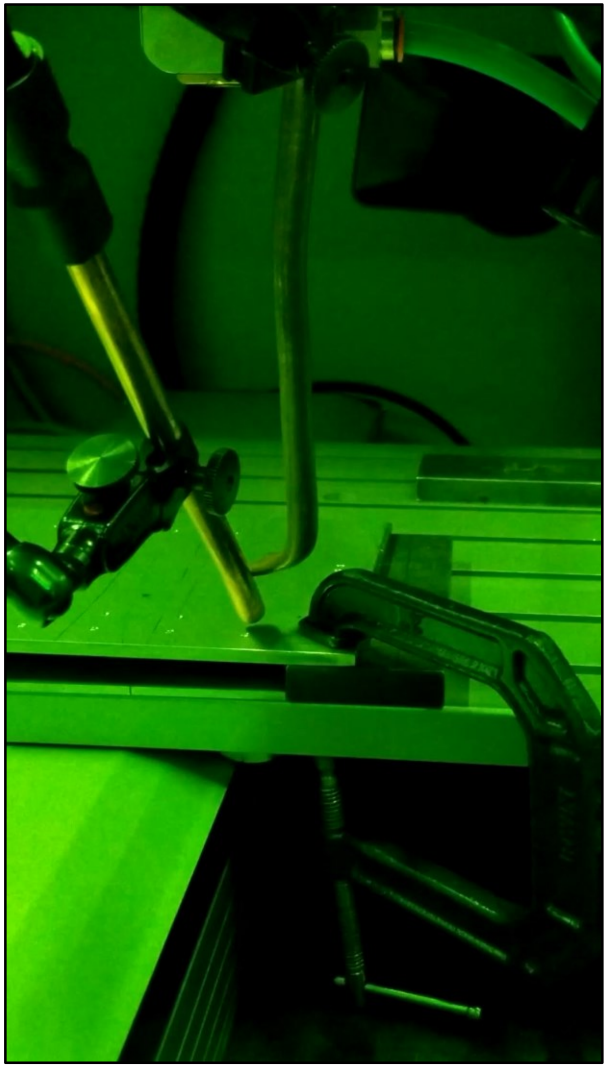
THE OHIO STATE UNIVERSITY

LBW Parameters

IPG YLS – 4000

- 207.5±2 mm working distance
- 0.5 mm spot size
- 0° beam angle
- Ar plume suppression 15 CFH (trailing)
- 304 S.S.



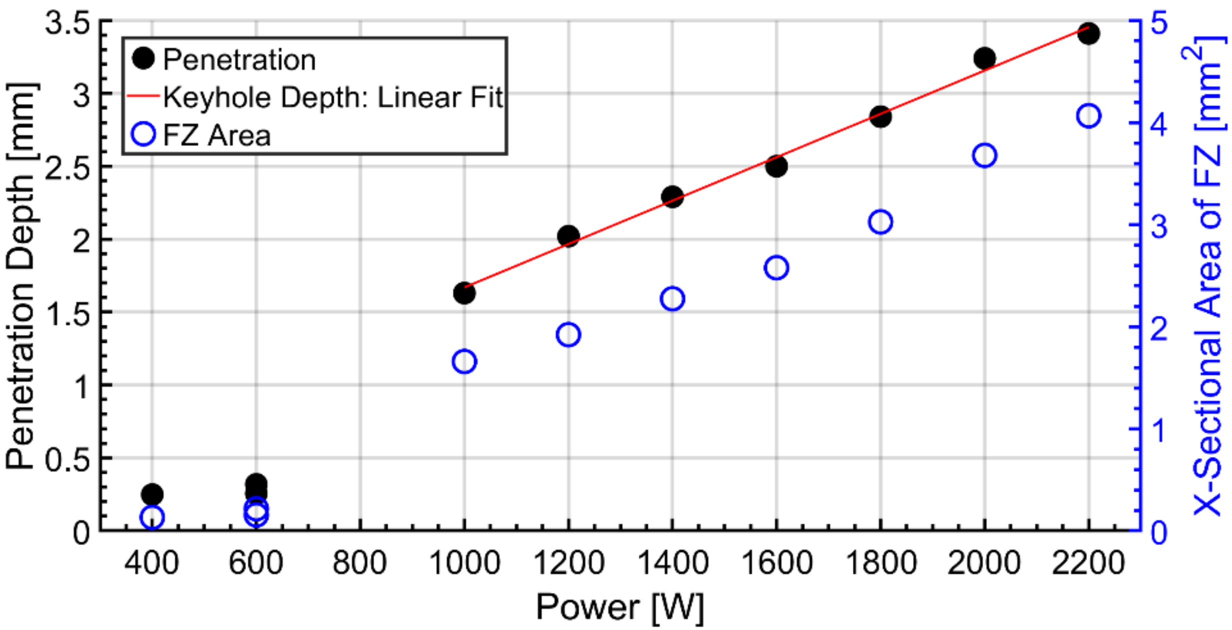


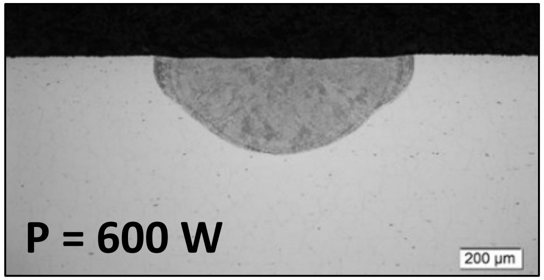
*slowed by 10 fps

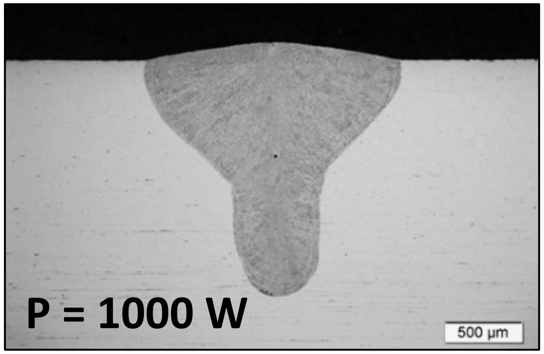
LBW Results on 304 S.S.

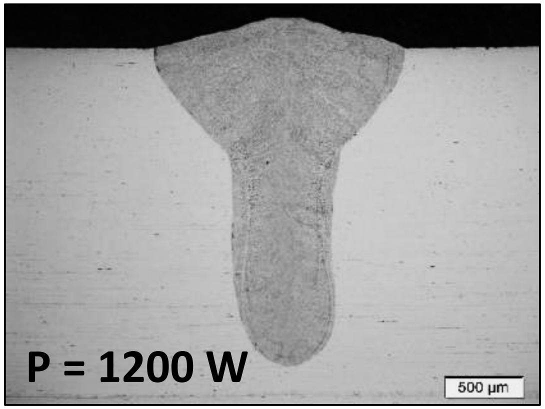
Travel Speed = 25 mm/sec

Interaction Time (t_i) = 20 msec





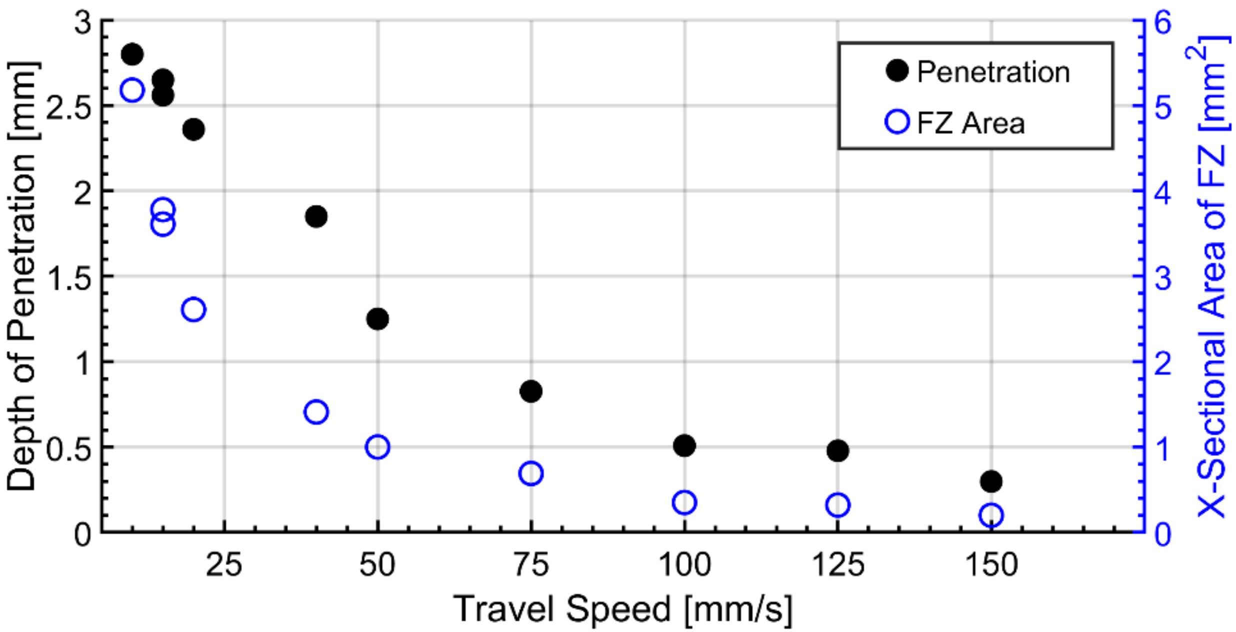


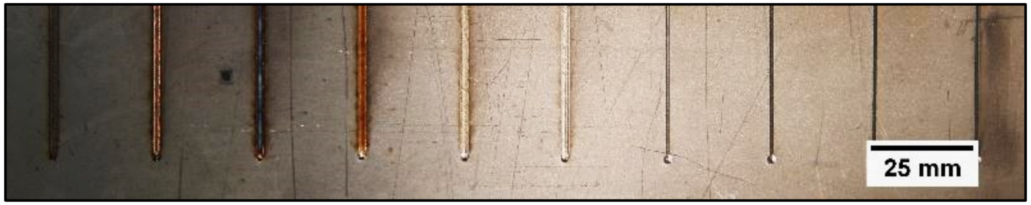


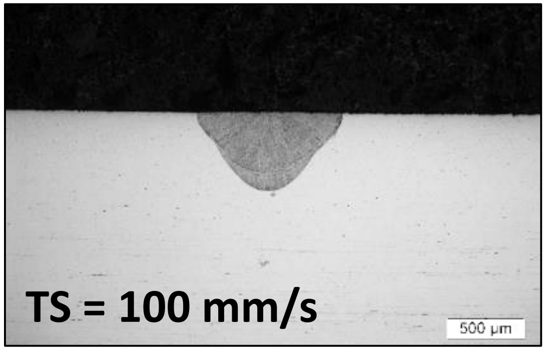
LBW Results on 304 S.S.

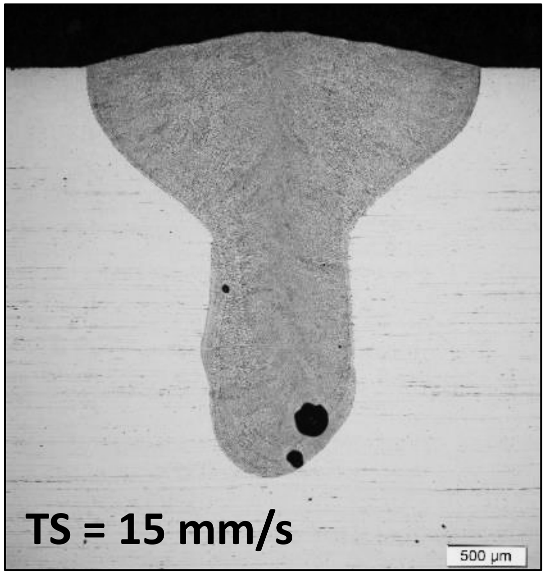
Power = 1400 W

Power Density = 7.1 kW/mm^2





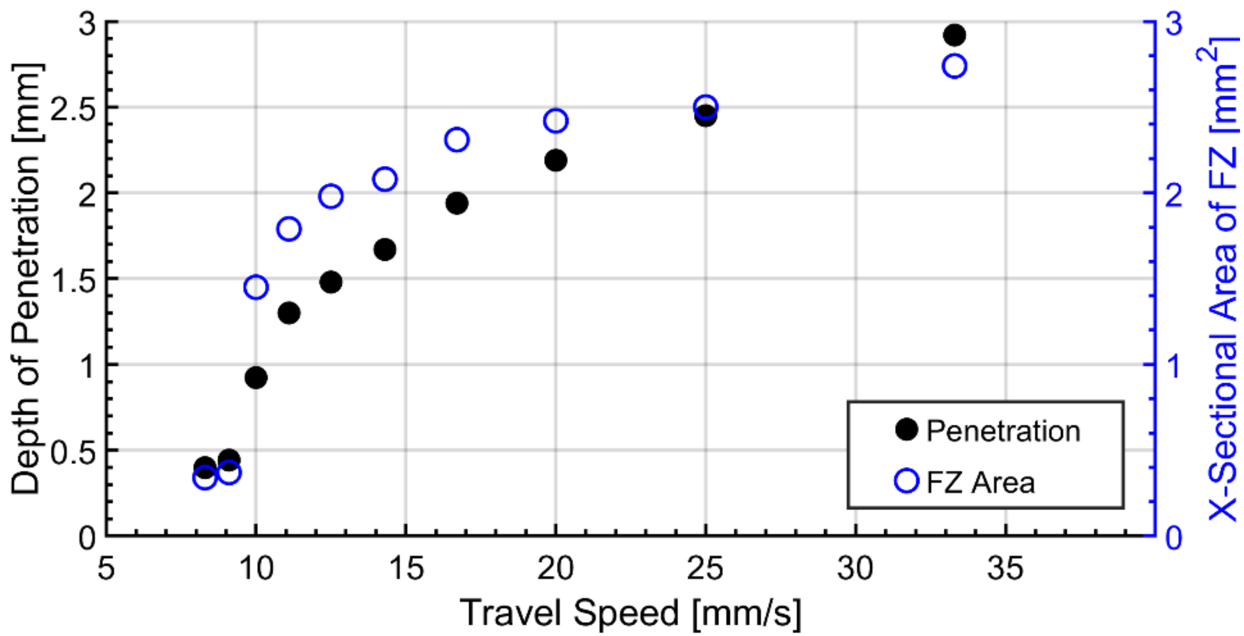


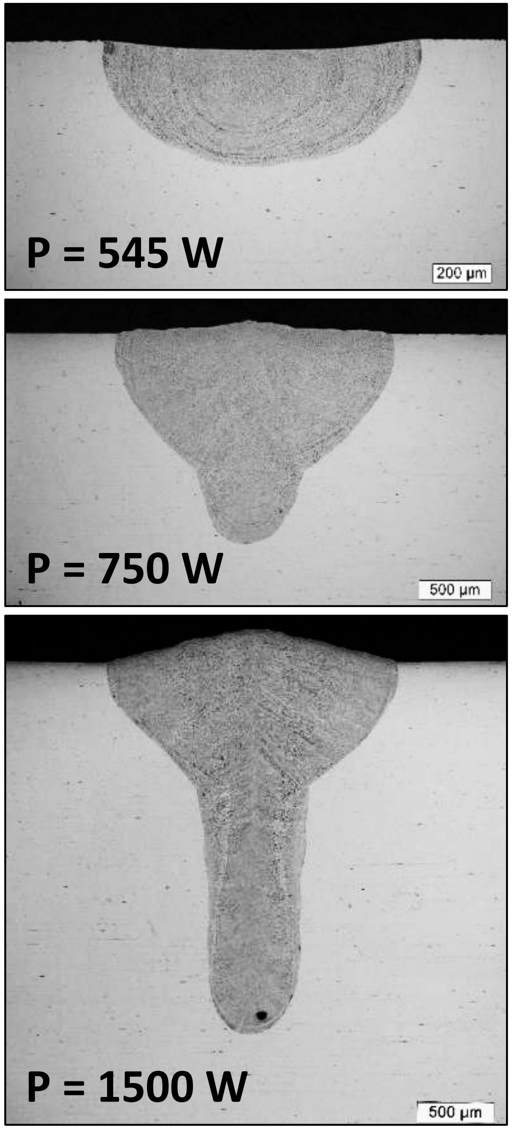


LBW Results on 304 S.S.

SPE = 30 J

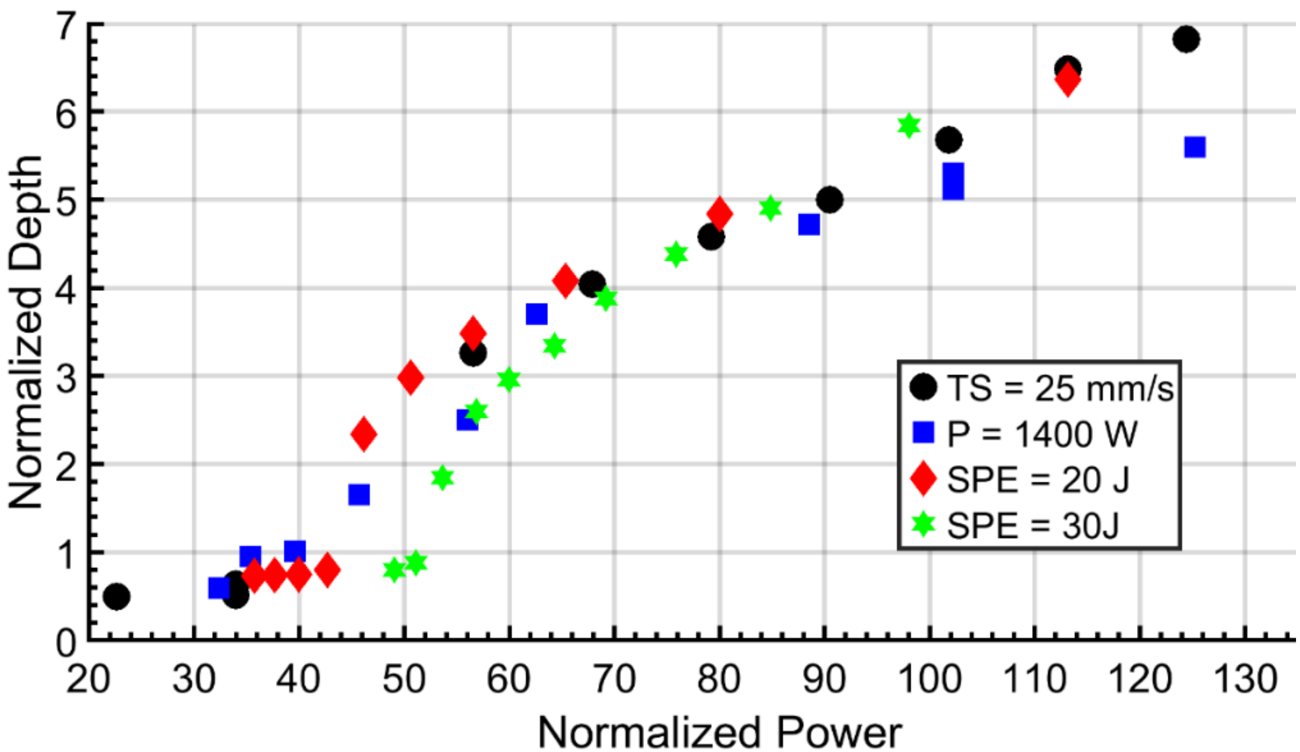
Energy Density = 153 J/mm²





LBW Results on 304 S.S.

- **Data Normalized Based on Hann et al. [3] Equations**



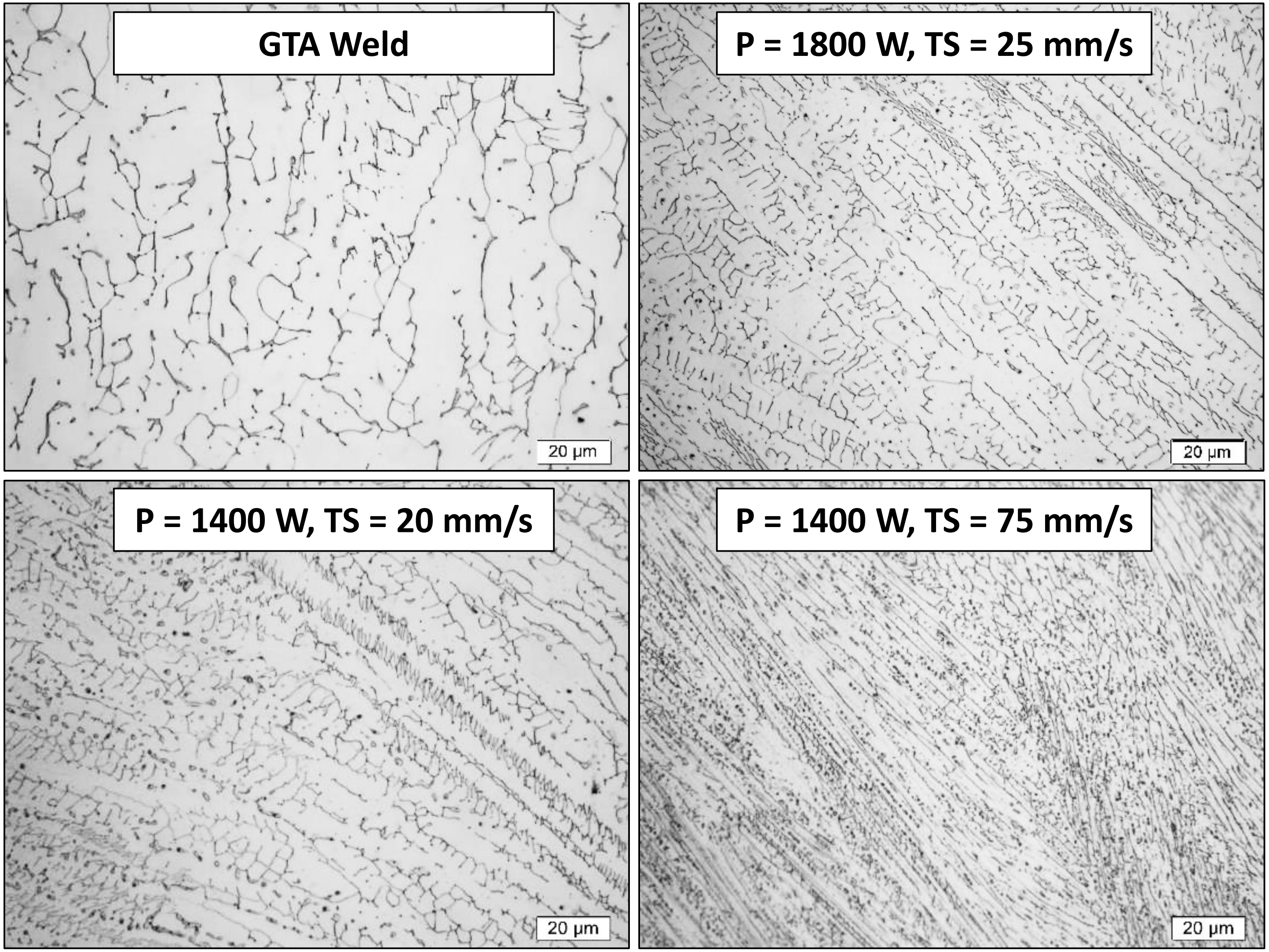
$$Normalized\ Depth = \left(\frac{\delta}{\sigma}\right)$$

$$Normalized\ Power = \frac{B * P}{sqrt(\sigma^3 U)}$$

$$B = 1x10^{-7}\frac{s^{1/2}}{Jm^2}$$

** For 304 S.S.*

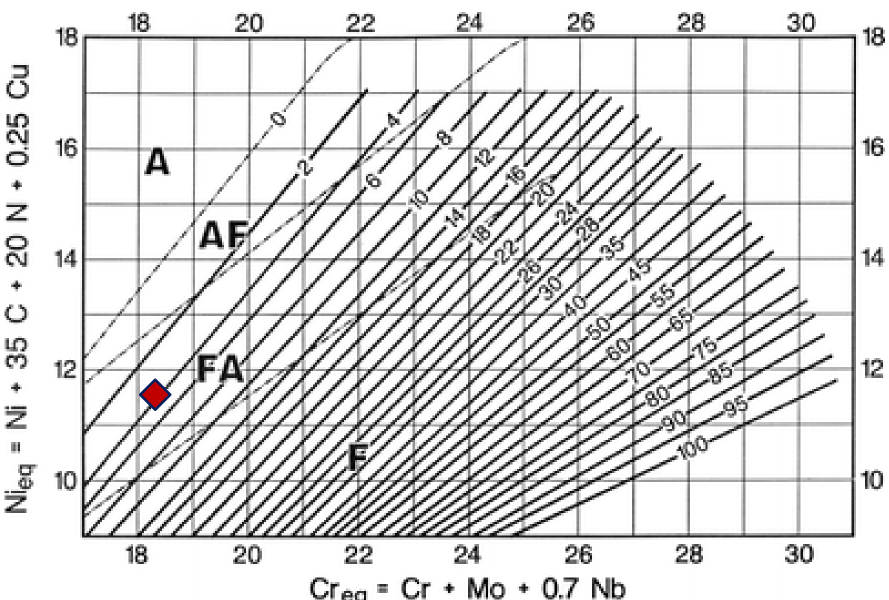
LBW Results: Microstructure Evolution



EBW Parameters

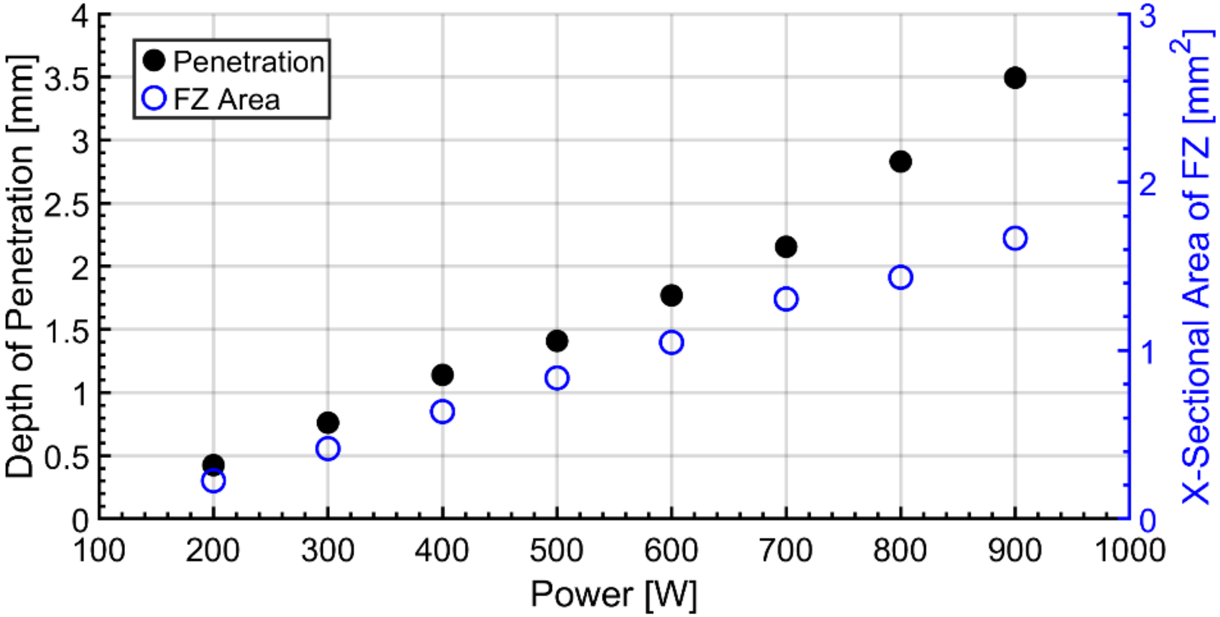
Pro-Beam K10

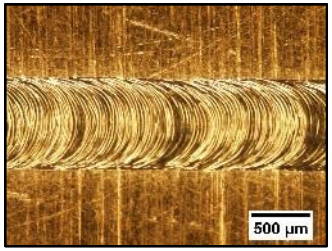
- high voltage system
- ≈200 mm gun to work distance
- 0.5 mm beam diameter
- high vacuum (< 1×10^{-4} torr)
- 304L S.S.

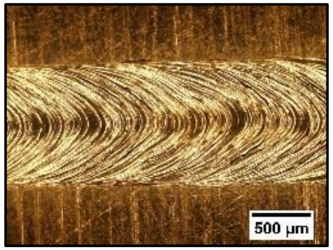


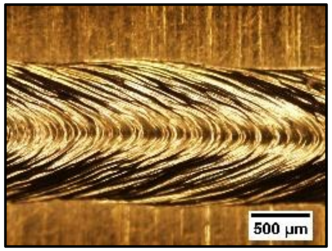
EBW Results on 304L S.S.

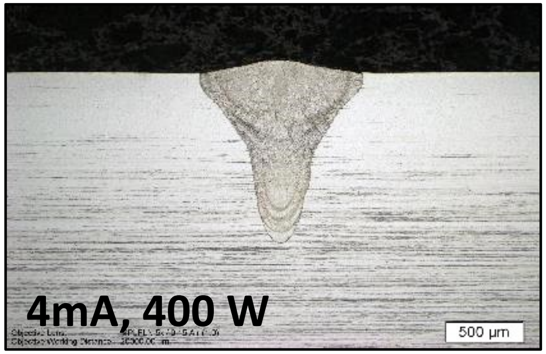
Constant Voltage = 100 kV
Constant Travel Speed = 25 mm/s

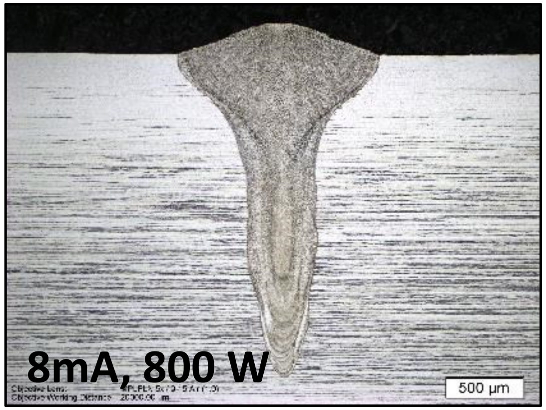






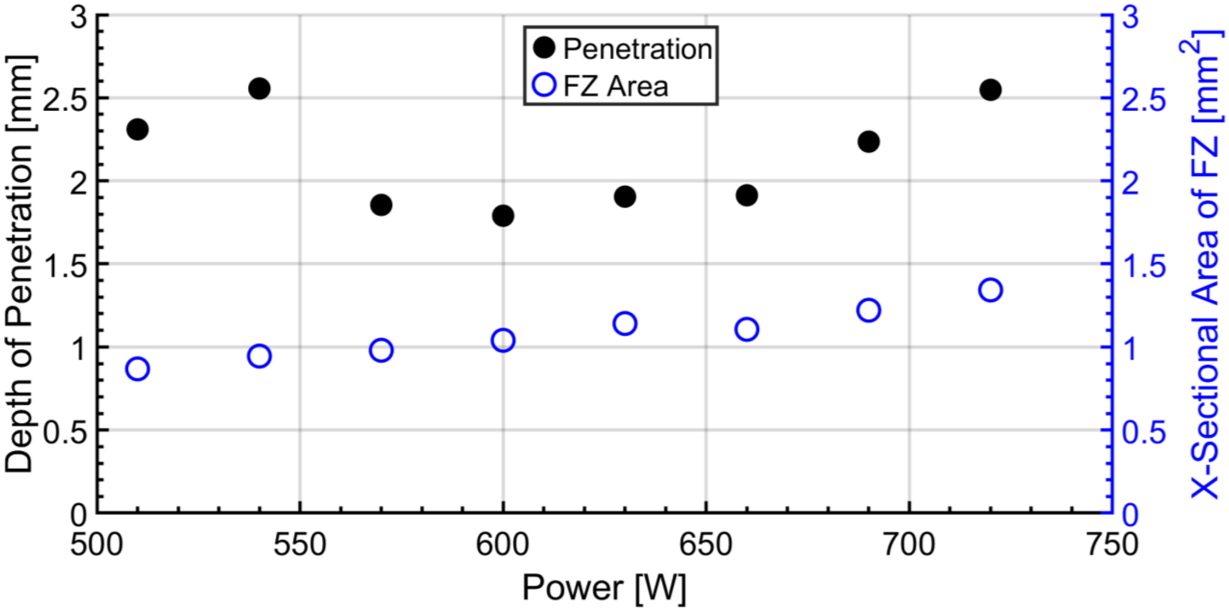


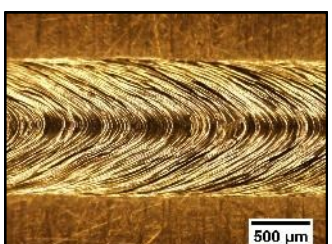


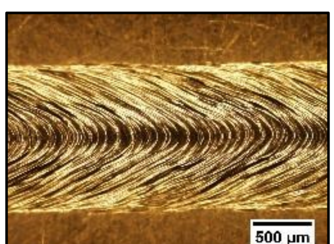


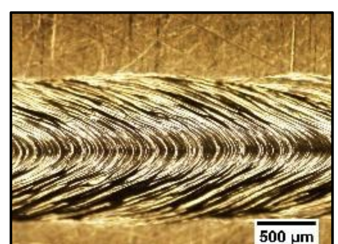
EBW Results on 304L S.S.

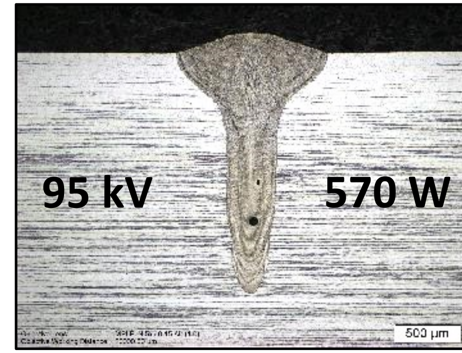
Constant Current = 6mA
Constant Travel Speed = 25 mm/s

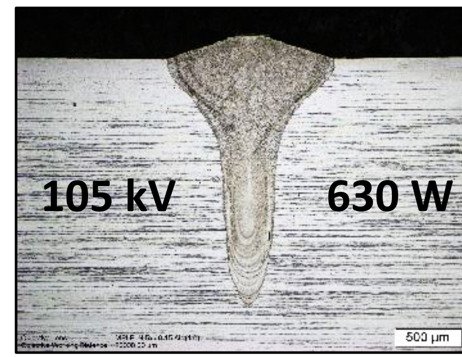


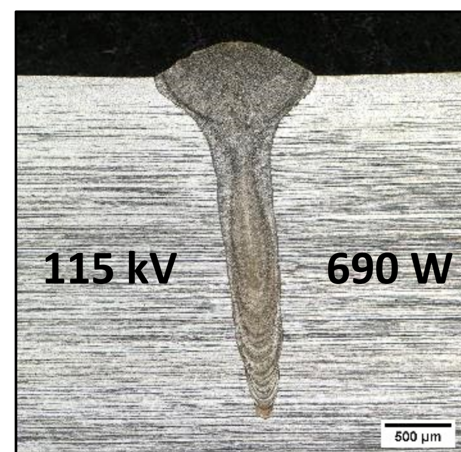






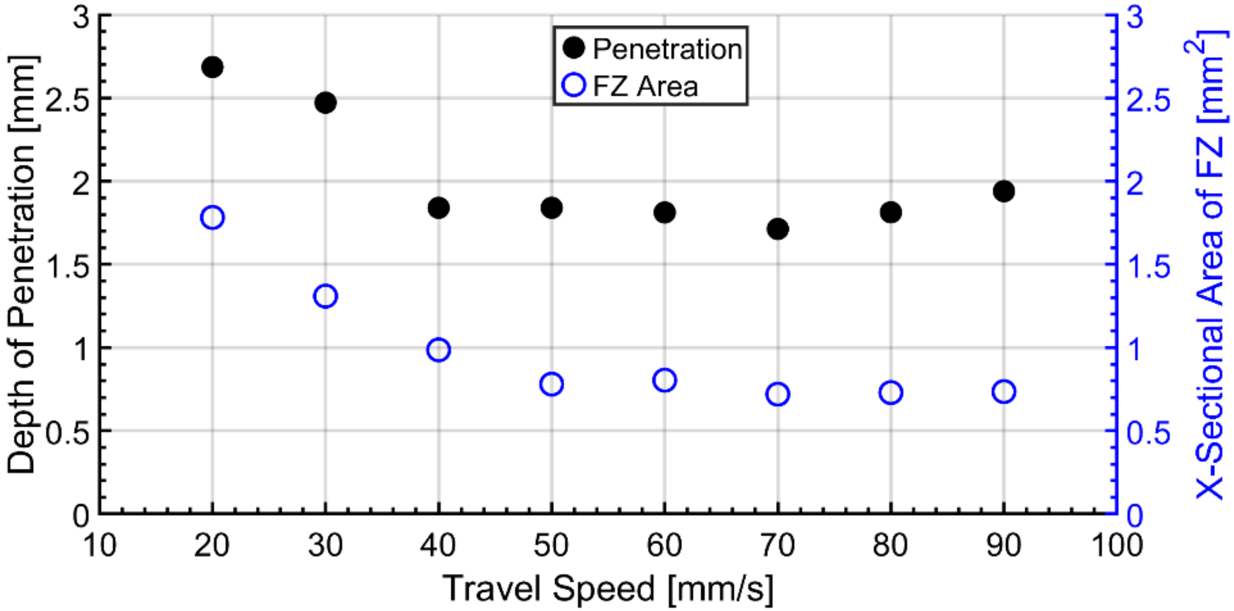


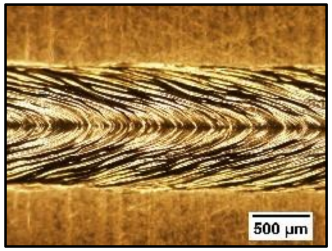


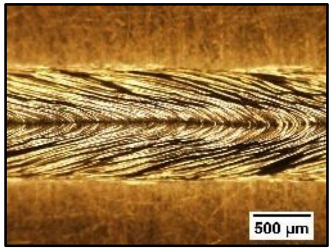


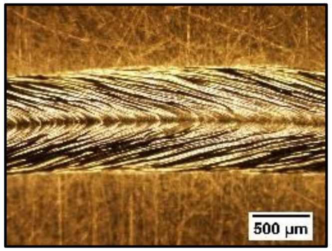
EBW Results on 304L S.S.

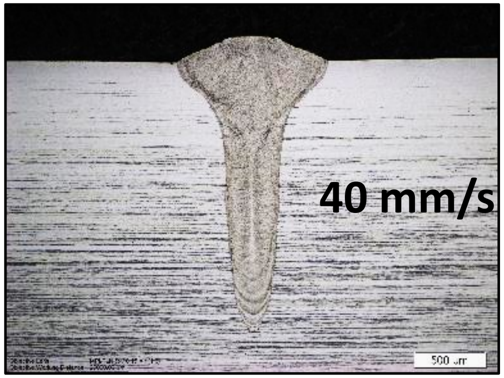
Constant Current = 6mA
Constant Voltage = 100 kV

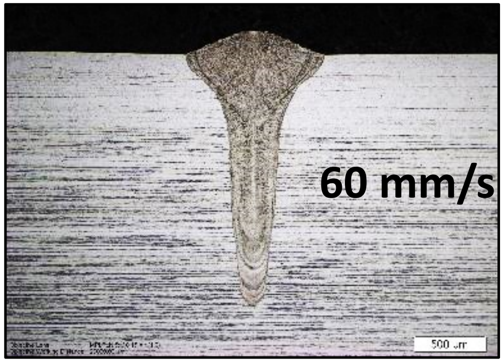


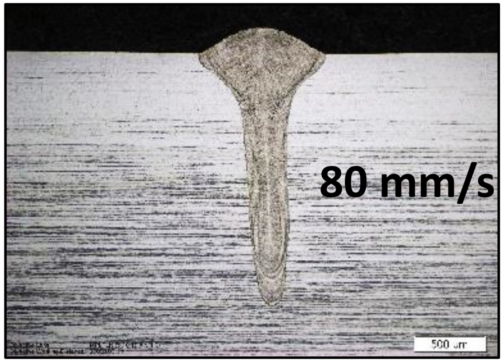












Conclusions

LBW

- Constant travel speed and beam diameter produced a linear increase in keyhole penetration depth
- Constant power showed a non-linear decrease in penetration depth
- Travel speed has largest influence on microstructure variations in 304 S.S.

EBW

- Increasing current showed an increase in penetration depth
- Increasing voltage showed no correlation with penetration
- Penetration decreased with constant power until travel speeds were in excess of 60 mm/s

Future Work

- Perform in-depth characterization of the weld metal microstructures
  - Analyze solidification modes, phase fractions, and dendrite arm spacing
- Measure the beam profile of the laser
- Complete laser welds on Ti-6Al-4V and 304L
- Understand the data to produce a predictive tool to determine weld geometries based on input parameters and material properties
- Produce microstructural maps for solidification profiles and phase fractions

References

[1] W. J. Suder and S. W. Williams, “Investigation of the effects of basic laser material interaction parameters in laser welding,” *J. Laser Appl.*, vol. 24, no. 3, p. 032009, 2012.

[2] D. B. Hann, J. Iammi, and J. Folkes, “A simple methodology for predicting laser-weld properties from material and laser parameters,” *J. Phys. D. Appl. Phys.*, vol. 44, no. 44, 2011.

[3] D. B. Hann, J. Iammi, and J. Folkes, “Keyholing or Conduction – Prediction of Laser Penetration Depth,” *Proc. 36th Int. MATADOR Conf.*, vol. 22, no. 0, pp. 275–278, 2010.

[4] J. C. Lippold, “Solidification Behavior and Cracking Susceptibility of Pulsed-Laser Welds in Austenitic Stainless Steels A shift in solidification behavior under rapid solidification conditions promotes an increase in cracking susceptibility,” *Weld. J.*, vol. 73, no. 6, pp. 129–139, 1994.

[5] J. W. Elmer, S. M. Allen, and T. W. Eagar, “Microstructural Development during Solidification of Stainless Steel Alloys,” *Metall. Trans. A*, vol. 20A, no. October, pp. 2117–2131, 1989.

[6] D. J. Kotecki and T. A. Siewart, “WRC-1992 Constitution Diagram for Stainless Steel Weld Metals : A Modification of the WRC-1988 Diagram,” *Weld. J.*, no. May, pp. 171–178, 1992.

Acknowledgments

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IPG Photonics

Kevin Arnold, Eric Stiles, Erin Lalinsky

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